Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Cybernetics

BACHELOR THESIS

Economy-Focused Multi-Player Strategy Video Game

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Supervisor: Mgr. Radek Píbil

Study Programme: Cybernetics and Robotics

December, 2013

Czech Technical University in Prague
Faculty of Electrical Engineering

Department of Cybernetics

BACHELOR PROJECT ASSIGNMENT

Student: Zbyněk Bambušek

Study programme: Cybernetics and Robotics

Specialisation: Robotics

Title of Bachelor Project: Economy-Focused Multiplayer Strategy Video Game

Guidelines:

1. The task is to create a multiplayer strategy video game, in which the goal is to reach a dominant position in the market.
2. The game will support multiple players of which some, none, or all players can be artificial.
3. The game will employ various protocols from the negotiation theory and auction theory and artificial players will take part in them rationally to achieve the game goal.
4. The game will be presented through a graphical user interface.
5. The economy will be based on exchange of multiple kinds of resources, which will be necessary to construct buildings and conduct research.
6. Players will build buildings of various types, manufacturing a wide range of products.
7. Players will allocate money to various research projects affecting parameters of buildings and interaction with other players.

Bibliography/Sources:

[1] Yoav Shoham, Kevin Leyton-Brown: Multiagent Systems – Algorithmic, Game-Theoretic, and Logical Foundations. Cambridge University Press, 2009.
[2] Stuart J. Russell, Peter Norvig: Artificial Intelligence – A Modern Approach (3. internat. ed.), Pearson Education, 2010.

Bachelor Project Supervisor: Mgr. Radek Píbil

Valid until: the end of the winter semester of academic year 2013/2014

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ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
Fakulta elektrotechnická
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Prague, January 10, 2013

České vysoké učení technické v Praze
Fakulta elektrotechnická

Katedra kybernetiky

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

Student: Zbyněk Bambušek

Studijní program: Kybernetika a robotika (bakalářský)

Obor: Robotika

Název tématu: Počítačová strategická hra pro více hráčů zaměřená na obchod

Pokyny pro vypracování:

1. Student vytvoří počítačovou hru, ve které bude úkolem v obchodním prostředí získat dominantní obchodní postavení.
2. Hra bude podporovat více hráčů. Hrát budou moci výlučně umělí hráči sami, umělí hráči s jedním živým hráčem či jen živí hráči.
3. Student využije ve hře různých protokolů teorie vyjednávání a aukcí a umělí hráči se jich účastní racionálně k dosažení vítězství ve hře.
4. Hra bude prezentována pomocí grafického rozhraní.
5. Ekonomika bude založená na několika druzích surovin potřebných ke stavbě budov a výzkumu a obchodu s nimi.
6. Hráči budou stavět budovy různých druhů, produkující výrobky různých druhů.
7. Hráči budou financovat různé výzkumné projekty ovlivňující parametry budov a interakci s ostatními hráči.

Seznam odborné literatury:

[1] Yoav Shoham, Kevin Leyton-Brown: Multiagent Systems – Algorithmic, Game-Theoretic, and Logical Foundations. Cambridge University Press, 2009.
[2] Stuart J. Russell, Peter Norvig: Artificial Intelligence – A Modern Approach (3.internat. ed.), Pearson Education, 2010.

Vedoucí bakalářské práce: Mgr. Radek Píbil

Platnost zadání: do konce zimního semestru 2013/2014

prof. Ing. Vladimír Mařík, DrSc.
vedoucí katedry

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děkan

V Praze dne 10. 1. 2013

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Firstly, I would like to thank sincerely to my supervisor, Mgr. Radek Píbil, for great help, support and patience during my work as well as in setting the topic.

I would also like to thank my friends, colleagues and other people who helped me with interesting ideas, suggestions or support.

A special thanks belong to my family for supporting me in my studies and in my life.

Prohlášení autora práce

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze dne 1. 1. 2014 ....

Zbyněk Bambušek
....
Podpis autora práce

Abstract

The main contribution of this thesis is a game that allows each player to learn about auctions, rational behaviour in auctions and auction algorithms. It is meant to translate auction theory into a more easily understandable form by letting players apply their understanding during the game. The thesis also discusses the impact of omission of various assumptions like independent valuation of goods by agents or adoption of non-risk-neutral strategies that lead either to risk-avoidance or risk-seeking. It also describes the process of designing the artificial intelligence and gives reasons for favouring certain approaches over others.

The game can serve as a basis of a more complex project, since its design and implementation can be expanded on. The project allows for auctions, designs, implementation of the AI etc. to be complemented by new ideas, and there is also a possibility of adding new types of buildings, auctions etc. This is also true for ways of upgrading buildings and research which might also be improved. In this way the game could be brought even closer to reality and could potentially bring deeper understanding of auctions and economical behaviour. This project could thus be used as a basis for an even more complex and intriguing computer game.

Abstrakt

Hlavní přínosem této práce je hra, která umožňuje každému hráči učit se o aukcích, racionálním chování v aukcích a aukčních algoritmech. Hra převádí aukční teorii do lépe pochopitelné formy a tím umožňuje hráčům, aby během hry aplikovali své poznatky. Práce také rozebírá důsledky vynechání různých předpokladů jako nezávislost ohodnocení zboží agentem nebo strategií zahrnujících riskatní postoj, závislosti na nichž je agent buď nakloněný riskování, nebo zdrženlivý. Práce také popisuje proces navrhování umělé inteligence a udává důvody pro použití určitých typů řešení namísto jiných, původně zvažovaných.

Hra může sloužit jako jádro rozsáhlejšího projektu, vzhledem k tomu, že její návrh a implementace je možno rozšířit. Projekt umožňuje rozšířit aukce, implementaci umělé inteligence atd. o nové myšlenky. Rovněž je možné přidat nové typy budov, aukcí atd. To samé se týká způsobů vylepšování výzkumů a budov, které mohou být rovněž vylepšeny. Tímto způsobem se hra může více přibližovat realitě a přinášet o něco hlubší pochopení aukcí a chování ekonomiky. Tento projekt se tak může stát základem pro komplexnější a ještě poutavější hru.

Contents

List of Figures

List of Tables

1 Introduction

The aim of this thesis is to study the application of multi-agent systems and auction algorithms in creating an economy-focused multi-player strategic video game. The game presents three different types of auctions for the players to participate in and introduces the basics of auction theory. The point of the game is to introduce the player to the differences between auction types in an entertaining way, playing against the AI. Moreover it makes use of the same algorithms that can be later encountered in different circumstances and therefore can be useful as a demonstration of their functionality.

It is useful to study auction algorithms since they are frequently used in auction houses, markets and other places concerned with buying and selling goods. They can also be used for solving of the scheduling [1] and assembling [2] problems. In the game the players use auctions to trade resources which are produced in their mines. [4].

The multi-agent systems also have a wide range of applications. They are used for example to create the AI of various games that usually replaces the human as an opponent [4] Furthermore, the motivation for studying multi-agent systems often stems from interest in artificial(software or hardware) agents, for example software agents living on the Internet as the Internet can be viewed as the ultimate platform for interaction among self-interested, distributed computational entities or hardware agents for example autonomous robots in a multi-robot setting. [4] The multi-agent systems are also used in applications that include transportation or logistics [2] and in the film industry. [6]

1.1 Goals

The three main objectives of the game are:

- To design an economically-focused multi-player game and create a competitive environment, where all the players have equal starting positions and their main mode of interaction is through various types of auctions in which the players trade resources which they produce.
- To create the game, including the implementation and graphics necessary to present the game to the player.

[1] example: Each runway at an airport can only accommodate one plane at a time. Airlines (agents) have costs related to delay of their flights (task). The task is to use the runways as efficiently as possible, with minimum time between the flights. [1] (source includes more examples).

[2] example: A manager employs three people (agents) in three different cities. He needs to move them to three other cities. Of course the cost of fuel differs with distance. The task is to determine where to send which agent in order to minimize airfare.

- Let the players learn about the basics of auctions through playing the game.

1.2 The Structure of the Thesis

The thesis is structured as follows:

- The first part deals with the game system, the goals and principles of the game. Furthermore it explains the drawbacks of the ideas that were eventually not used. It deals in detail with the individual parts of the game such as the buildings, research, resources etc. Furthermore, it explains the game evaluation and the IPs.
- The aim of the second part is to introduce and discuss the English, Vickrey and Dutch auctions and to present the auction definitions.
- The third part focuses on the artificial player and describes how he decides on a game strategy with regard to which he invests in the buildings and research.
- The fourth part deals with the auction algorithms used in the game and the ways in which the AI player bids in the auctions. It explains when the result of an auction is advantageous for the bidder and when for the seller, how the bidder acts in the auction and how the risk attitude and dependence of agent values influence his decisions.
- The last three chapters sum up the results, consider the future work and improvements that the game may include and provide a conclusion to the thesis.

The contents of the enclosed CD are described in the appendix. [39]

2 Last Planet - The Game

We will now discus the game default setting and starting conditions. We will also include descriptions of buildings and research used in the game and include an example of the process of the game.

2.1 The Game Setting

Goal of the Game Last planet is an Economy focused multi-player strategy video game. The goal of the game is to secure dominant economic position in the trade with resources by building and improving a city (for example by building mines and doing research) and trading with other players. At the start of the game the players have the same conditions, the starting coordinates being set at random. The game setting pushes players to focus on one resource. Therefore the player has to choose a resource at the outset of the game and adopt a corresponding strategy

Game Evaluation The first problem to solve is evaluation. For this purpose we defined influence points (IP). Each time any player spends his resources, wins or creates an auction or in any way influences the game, he earns influence points (IP). Since this type of evaluation for the most part depends on the market, it is necessary for the player to participate in transactions that are presented in the form of auctions, which consist the main part of the game. Throughout the game the IPs of the player are compared with the others'. When the best player's earn reaches 100+X%[3] of the second player's earn, the game ends and he wins.

Game Progress Structure At the start of the game each player has the same starting conditions except the position which is selected randomly. The players build different types of *buildings*[4] In order to unlock the research lab, the players have to build a power station and upgrade it at least to level 3. When the research lab is finished, the players can start investing in *research*. Each player starts with the same default amount of *resources*. Creating an auction in this part of the game is extremely disadvantageous due to the fact that the player has no possibility to invest *money*.

In an early stage of the game each player should decide which resource he will be focused on. If the player focuses on one resource the total production at the end of the game will be much higher, because the increase between levels is not linear[5] the other resources can be obtained in auctions. Each player starts to upgrade the buildings as well as the research lab, which unlocks

[3] X is optional and can be set before the game starts ($X \in \langle 20; 100\rangle \wedge 10|X$). The available definitions of economic dominance proved unsuitable for the purposes of this game since they pertain to a market consisting of 50 or more firms and the game is structured for 2 to 8 players. [7] [8]

[4] Terms written in italics in this paragraph are later discussed in detail.

[5] further discussed in 2.2.

the research. However it is not yet advantageous to invest in them. The upgrades bring money to the player. The danger that appears here and lasts until the end of the game is the limits of *population and energy*. They are often overstepped and then the player has to *avoid sanctions*. It is still unlikely to see an auction in this part of the game.

In the middle of the game the players usually have more of certain resource then they need and therefore the first auctions are created. The game offers three types of *auctions* - English, Dutch and Vickrey. In this part of the game the player still has the possibility to build buildings but can also start upgrading the research. In this or the next phase of the game certain buildings can be *rebuilt* in order to save space or improve their parameters.

By the end of the game there is no free area left to build buildings and *place saving* takes place. At this point there are usually many simultaneous auctions and the players should concentrate on doing the research.

At any time in the game the players may use *direct trade* in which the players can change their money for resources or resources for money at disadvantageous *exchange rates*. The price set for the individual resources helps the players to assess their value in the game.

At the end of the game the players have an opportunity to see their exact IPs, which are not shown during the game. The winner of the game is the player who gained the most IPs.

Figure 1: Graphic representation of the final score

Resources Earning and Valuation Players can spend money, stones, metals and minerals. Each resource has different value: stones - $IP/1000$ units,metals - $1.5IP$s$/1000$ units, minerals - $3IP$s$/1000$ units and money - $IP/1000$ units. Some resources are easier to earn so their value is lower. It cannot be said which resource is the most advantageous to focus on because it depends mainly on other players' selections.

Money After upgrading a building or conducting a research, the player earns a certain amount of money according to the level of that building or research after the upgrade. It is not enough to hold the game in optimal state since updating gradually becomes more and more complicated

and eventually there is no money income in the game. It would not be logical if money, which is needed to do research, to participate in auctions and to construct some of the buildings, were unreachable.
For this reason each player also earns money through taxes. At certain time intervals, players receive money depending on the population they have. This income is calculated logarithmically due to fact that the main population increase comes from buildings and rises exponentially.

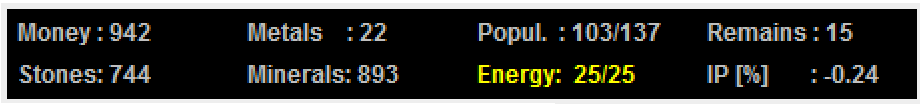

Figure 2: Graphic representation of the resources

Energy and Population As figure 2 shows, population and energy are rather similar to resources, but unlike them they can be exceeded.

If a part of the player's population is not accommodated, it will reflect in problems such as strikes and riots, which in the game result in lowering of the production. The extent of the decrease is determined according to the degree to which the population is exceeded (a small degree of overpopulation would not lead to great protests). The point of reference is the ratio between the lodging at the disposal and the lodging in demand, which, if the population is exceeded, is always lower than 1. Moreover, the process should not be linear, since if there were 25% living outside the city, the situation would be much calmer than at 50%, in which case it would be near fatal. For this reason the ratio is considered square. This means that if the population is exceeded by 5% (which is relatively high), the decrease in production is not 5% but 9%, in order to approach reality. The divergence increases in a logical way, for example at 50% the production is only a quarter of its original amount.

If the energy consumption is exceeded, the player is forced to buy it for its market price. Energy as such cannot be traded, but in the game its exchange ratio is determined by the amount owned by the other players and the amount of energy available, same as the other resources. All the resources can be bought outside auctions, however their price is very high, making it disadvantageous[6].

How to Avoid Sanctions Since the repercussions for exceeding the limits are fairly severe,the players can reduce the production of certain buildings, since lower production lowers the energy consumption and requires less population. It allows the players to reduce losses by making the reduction in the district where it is most advantageous. The Research lab does not have any

[6] further discussed below

production but its activity can also be reduced, which affects its functionality in a different way. For example if a player reduces the Research lab which is on level 3 to 60% of its activity he will not be able to upgrade research to level 2 or more. If he leaves it at 70% he will not be able to upgrade to level 3 but he can upgrade to level 2.

Remaining Area and Score As demonstrated in the figure 2 there are two other values in the panel of resources.
Remaining area states the amount of upgrades that remains until the starting area is fully occupied. The research lab is the only building which does not require any building area in order to be upgraded.
IP percentage shows how many percent behind the best player's score the player is. If the player selected has the highest score the sign is negative and it shows his lead compared with the second player.

Direct Trade The players can see the exchange rates of the resources and may use the direct trade, avoiding the auction system. However the direct trade is very disadvantageous since the other players, especially artificial, may use it for calculating their bids. Exchange rates are calculated from the respective amounts of the resources in the market.

- First of all the combined income of all the players for all the resources is converted to IPs.
- Then the player takes the total game income for one resource (in IP) and divides it by the combined income to get the ratio between them.
- In the next step the result is divided by 1/3, which gives us the proportion between the ideal state and the real state.
- This proportion is finally used to calculate the exchange rate

The exchange rate is counted as:
$ER_b = 3.R.RV$/unit and $ER_s = \frac{R.RV}{3}$/unit, (1)
where R is the mentioned proportion between ideal and real states.
It means for example for metals:
$ER_b = \frac{9RV_{st}^2.Gain_{st}}{RV_{st}*Gain_{st}+RV_{me}*Gain_{me}+RV_{mi}*Gain_{mi}}$/unit and
$ER_s = \frac{RV_{st}^2.Gain_{st}}{RV_{st}*Gain_{st}+RV_{me}*Gain_{me}+RV_{mi}*Gain_{mi}}$/unit.
ER_b is the exchange rate - when buying for each unit of the purchased resource the player pays ER_b unit(s) of money. In the same way, ER_s is the exchange rate when the player is selling (for 1 unit of a resource he gets ER_s of money). Constant 3 in the equation (1) is just a reducing constant to make the trade less advantageous which should force players to participate more in

auctions.

The last problem to solve regarding direct trade is the energy cost. As we already mentioned in the previous paragraphs, the penalization for exceeding the energy limit requires the energy value to be set. The value for one unit of energy is set to:

$ER_b = \frac{PL_{max}}{MN}$, where PL_{max} is the amount of energy in the player's possession, MN is the amount of energy in the whole game.

Figure 3: Graphic representation of the direct trade

Influence points as Evaluation Since the IPs, which decide the game, are counted from the start of the game, there is a danger that the first player that builds a building automatically wins the game. The first possible solution for this problem was to start counting after a certain amount of time, when all the players will have reached a minimum level. However, this solution lacked realism, since there is no reason to start comparing the incomes only after a certain period of time. When a firm comes to the market it has to take the rivals in consideration from the start. The solution that was eventually used supposes that the players possess the building area from the start, including basic facilities necessary to live, and therefore they don't start with $0IP$.

At first the game was meant to be time-limited and end after a set amount of time. The advantage of this option was that the game would be strictly timed. However, it would mean that the game could end before any of the players obtained economical dominance, therefore resulting in a tie. Moreover, it does not encourage the players to be as competitive as in the case of finishing by real percentage dominance of IP.

Finally there was a possibility to include a military part in the game and also to add an option of transporting resources between players by ships. This would allow the players to declare war or steal resources in towns or during the transport. It would also allow the players to trade units and weapons and to finish the game by destroying an enemy city. Nevertheless, it does not comply with the aim of this project, which is to create a game with strictly economical goals.

Influence points Distribution In this section we will discuss how the player earns IPs. Each time the player invests his resources he earns IPs equal to the real value of the resources spent. Besides this there are two other ways to obtain IPs.

For creating a successful auction the player earns 1/10 of the real value of resources offered in IPs.
The amount 1/10 may seem too much, however the point of the game is that the players use the auctions, and therefore they have to be advantageous. Moreover using this setting the auction allows the player to sell the resources for less than their actual cost without disadvantaging himself.

If the player wins an auction he earns 1/10 of the real value of resources in the auction in IPs. This should again force the players to participate and allow them to offer more than the value expected since they gain extra IPs if they win.

Place Saving: After a certain amount of time the game reaches the limit when no more buildings can be built because there is no more area available. The player's aim is to have one mine at the highest level possible and this means reducing the levels of other buildings or reducing the investment to areas improvement. There are multiple ways of space saving:

- Reducing the Living area level. It must to be compensated by research (living area efficiency or automation in stones, metals, minerals research).
- Reducing the Power station level. Rebuilding or energy production or efficiency help to compensate.
- Investing in the research of areas improvement, which can gain extra space.

2.2 Buildings

Each player can build and upgrade several types of buildings. Upgrades can be understood as an extension of the area the building occupies. Degrading a building means vacating the occupied areas. Each extension or downgrade costs resources and affects the parameters of the building.

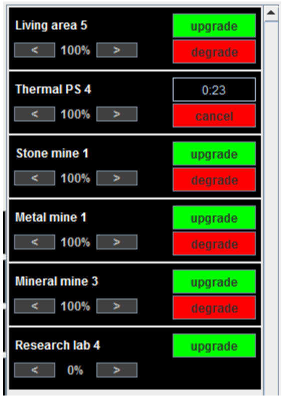

Figure 4: Graphic representation of the buildings in game

The growth of the parameters (which include cost and time) can't be linear. If it were, focusing on one resource would not be advantageous for the player. It is necessary to have the players focus on one resource in order to make the environment more competitive. In this work we use exponential increase with the basis of 1.3. This is applied to all the buildings, since with the exception of the Research lab all the buildings influence the production and it would be problematic if for example the parameters of the power stations increased linearly but the energy needed would increase exponentially. The research lab and the living area upgrades are also exponential since they both depend on other exponentially increasing values such as population or energy.

The number of buildings and building upgrades is limited with the exception of the research labs. This also makes it advantageous to focus on only one resource. At the start of the game each player builds buildings until he reaches the maximal limit. Then the players start to do research lab improvements until it is advantageous to downgrade one building and upgrade another in its place. Building downgrade is cheaper than upgrade and if the player does it no IPs are lost. The player does not earn any IPs from degrading buildings. The limitation on the number of buildings is imposed since the area of the city (default IP) is limited and at a certain point there is no more place to expand. Various types of buildings will now be described.

2.2.1 Living Area

This structure increases the player's population. It allows player to prevent sanctions of overpopulation. Moreover the player's population pays taxes which are the main way of earning money.

2.2.2 Power Stations

There are three kinds of power stations. Each player starts with a thermal power station which is less effective than the other kinds. Later he can do some research which allows him to build other types. The main purpose to increase the production of energy.

- The nuclear power station is more expensive than the thermal power station but the production is tripled.

- The fusion power station is more expensive than the nuclear power station but the production is four times bigger.

2.2.3 Mines

As there are three main resources that can be mined, there are also three types of mines. Their cost, production, research and needs should be balanced. The default cost of each mine is the same, however in different resources. All of the mines also have the same energy consumption and population required.

2.2.4 Research Lab

This structure allows the players to do research. In order to build a research lab it is necessary to have a thermal power station at level 3 or more.

2.3 Research

Research improves production, allows the players to build other buildings etc.

It can be upgraded in the same way as the buildings. If upgraded, it earns the player some research points and then it is possible to select out of different directions of upgrade. The amount of points earned is the same as the level of research. Each level raises exponentially the cost and time of the next upgrade. It is not permitted to have the level of a research higher than than of the research lab. Each player should be careful with upgrades. It is impossible to withdraw points that are once placed, and since the cost of research is high, the player might not be able to compete in auctions.

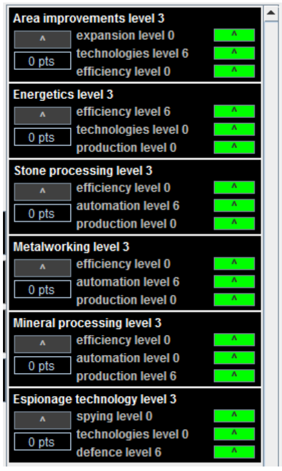

Figure 5: Graphic representation of the research in game

As opposed to the buildings, the effects of research improvement are not exponential. The increase of production is 1% of default production per point. The upgrades that lower the costs are usually set to -0,5% of current cost per point. Various types of research will now be described.

2.3.1 Energy Technology

There are three possible directions of research in this field. Energy efficiency reduces the power consumed by buildings. Energy technologies allow the players to rebuild their power stations. Rebuilding costs some money but may save a lot of building area. Energy production increases the production of the players' power stations.

2.3.2 Living and Building Area Improvement

In this field is is also possible to invest to three different areas. Space living area efficiency increases the player's population per level. Rebuilding allows the players to rebuild their living area and change its default parameters, which is a way to save space. The third possible direction is the expansion of the building area, which only comes to effect after a certain amount of points is invested in it, but when it does it doubles the player's building limit.

2.3.3 Stone, Metal or Mineral Production

Each of the mines presents three possibilities of improvement. Production and efficiency both function in the same way as in case of energy technology. The third possibility is the automation which reduces the population needed to work in the mine.

2.3.4 Espionage Technology

The last research also has three areas of development. By investing into spying the player increases his chance to gain private information about the movements of his opponent. Defence protects the player's private information from the other players.

3 Auctions

In this section we will describe the main auction mechanisms of the game and present the definitions of the auction types.

3.1 Auction Types Used in Game

For the purposes of this game we have chosen three of the most common auction types:
1) English auction (with or without buyout option available),
2) Vickrey auction,
3) and Dutch auction.
Each player can decide to use any auction type he wants.

1) English auction is a widely spread auction type. Unless he is the highest bidder, each agent can bid the minimal amount over the present bid, or more with the condition of overbidding the current highest bid. The minimal amount in the game depends on the real value of the goods. The ending in our case comes when no new bids are placed for a certain amount of time. When the auction ends the highest bidder wins the item and pays the highest bid. In some cases there is a possibility to win an item immediately without contest but usually by paying more money. This option is called buyout and in our case it is set by a seller.([3],pages 699–738),([4], page 331)

2) Vickrey auction is sealed-bid second-price auction. The bidders' bids are written on a paper and are not revealed. When everyone has bid, the auction ends, the winner being the highest bidder who pays the second highest bid that has been placed. ([4], page 331)

3) Dutch auction is an auction where the auctioneer gives the starting price of the object. During the auction the price decreases and at the moment when there is an agent who can afford to pay for the goods the auction ends. In the game the amount by which the price decreases depends on the real value of the goods. The winner is the one that accepted and he pays the current price. This type of auction is often used when the goods need to be sold quickly (for example if they are perishable).([3],pages 699–738),([4], page 331)

Multiple Resources in One Auction In the game there is a possibility to create an auction with more than one resource type. For English auction we used an algorithm with the same principle as the one described in MAS.([4],page 34) This auction system is set to bring maximal earnings to the seller. It means that each item is sold for the biggest offer even if it means that the different items in the auction are sold to multiple agents. It is in fact the same as if the auction were split into two or more auctions selling one item. In the other auction types all is sold to one bidder. This leads to higher revenue in case of the English auction because of the possibility to select only one resource. It maximises the revenue for each of the resource types offered and it is better than if two or more auctions were joint together.

3.2 Definition of Auction

Definition: Bayesian Game In the next step we will define the auction as a Bayesian game. Before that let us define Bayesian game using one of the definitions ([4], 6.3). Bayesian game setting is a quintuplet (N, O, Θ, p, u), where

- N is a finite set of n agents;
- O is a set of outcomes;
- $\Theta = \Theta_1 \times ... \times \Theta_n$ is a set of possible joint vectors;
- p is the probability distribution on Θ; and
- $u = (u_i, ..., u_n)$, where $u_i : O \times \Theta \mapsto \mathbb{R}$ is an utility function for each player i.

Mechanism of Bayesian game setting if a pair (A, M), where

- $A = A_1 \times ... \times A_n$, where A_i is a set of actions available to player $i \in N$ and
- $M : A \mapsto \Pi(O)$ maps each action profile to a distribution over outcomes. ($\Pi(O)$ is the set of all probability distributions over O)

Together, a Bayesian game setting and a mechanism define a Bayesian game.

Definition: Quasilinear Mechanism Because the utility functions in an auction setting are assumed to be quasilinear I will now define a quasilinear setting ([4],10.3.2). A mechanism in the quasilinear setting is a triple (A,χ,p).

- $A = A_1 \times ... \times A_n$, where A_i is a set of actions available to player $i \in N$,
- $\chi : A \mapsto \Pi(X)$ maps each action profile to a distribution over choices, and
- $p : A \mapsto \mathbb{R}^n$ maps each action profile to a payment for each agent.

Here we have just changed the definition of mechanism of Bayesian setting by splitting the function M into functions χ and p.

Definition: Auction as a Bayesian Game Next definition ([4],10.3.2) . Now basic auction environment can be finally defined. To define an auction as a quasilinear mechanism we must identify the following elements:

- set of i agents, where i = 1, ..., N,
- set of outcomes $O = X \times \mathbb{R}^n$,
- set of actions that each agent i can do A_i,
- choice function o that selects one of the outcomes given the agents' actions and
- payment function p that determines what each agent must pay given all agents' actions.

to complete the definition we need to specify two other components:
first of them is an utility function that quasilinear setting allows us to write ([4],10.3) $u_i(o, \theta_i) = u_i(x, \theta_i) - f_i(p_i)$. The function f_i indicates player risk attitude and u_i is utility function.
The second one is the way in which the agents make their evaluations. The auction algorithms that the AI player uses are independent private value or dependant private value. The selection of algorithm depends on the level of the AI player.

4 AI Players

In this section we will discuss the AI player's behaviour and explain the player's strategy as well as the way in which he improves his city.

Levels The game offers two levels of AI player with only a two differences between them.

- **Beginner**
  At the beginner level the production of the player is slightly reduced and he uses independent private values even though he is risk affected same as the intermediate player.

- **Intermediate**
  The intermediate player's production is not reduced and he uses dependent private values in the simplified form described in 5.4.2.

4.1 Basic Behaviour

Strategy: Each AI player first chooses a strategy, which is a vector of numbers that says which decisions the player will make. First of all the player decides on a resource focus strategy. This is represented by one number generated at random that says which resource the player will focus on. This is all that the player needs to know for deciding about the buildings. Depending on this selection, the other numbers are chosen. These numbers determine the way in which the research will be upgraded. The player focuses on producing the biggest amount of the main resource possible but in other research he still proceeds randomly. If an investment complying with the strategy is not possible the player randomly selects a way to upgrade any research. (Some research ways lock after reaching a certain level.)

It would also be possible to include the option of changing the strategy during the game. The idea of changing the main resource if the original resource is not produced enough in the game according to exchange rates was considered but rejected because refocusing to another resource would cost much more than it brings. It would mean stopping to upgrade the current main mine and building another. This would result in problems with the building area, which is quickly used up. Downgrades would be needed and that would mean further loss of resources and IPs. The result would be great delay behind the rest of players which may cause the loss of the game. It would also bring the problematic situations resulting from more players at once deciding to change resource. Such situation would just move the problem of unbalance from one resource to the other.

The AI players do not learn during the game. It surely is possible but it is rather the part of the future work than this thesis.

Saving Money: The first problem that the players have to solve is how much money to leave aside in order to stay competitive throughout all the auctions. The amount will change during the game as all the productions and auction values gradually rise. It can be easily defined as the expected value of the biggest auction that can appear. However in many cases this value is unknown. In such instance the player takes the double of the biggest bid that appeared as a point of reference. The reason for this is that if the auctions occur simultaneously and there are one to five auctions the player can place a bid in any of them.

Of course at the start of the game no bid has been placed yet, and therefore the AI players have some default amount of money that they leave aside. At the beginning of the game there is nothing to spend it on so the actual players cannot take an advantage of this fact. Players are allowed to invest money that they earn through direct trade, which takes place without auction but is disadvantageous.

Exchange Rates: The players can see the exchange rates which helps them to decide in certain situations, for example which mine to upgrade first. The exchange rates show the current value of the resource in the game and depends on production.

4.2 Building Selection

The first step is to browse all the buildings and to define and forbid those that are too expensive to build. Usually only one possibility remains. The decision depends on energy, population as well as the player's strategy. If the available selection still contains 2 or more buildings, the AI selects one at random.

Conditions for Building Selection: In order for the player to select a building it must satisfy these conditions:

- There must be enough space to build it. In case the limit is reached, no more buildings are allowed.
- The population and the energy limits must be high enough. The player will not overstep those limits if it is disadvantageous. He calculates the reductions needed to avoid penalizations and than decides if he benefits from the upgrade. If this condition is not satisfied he can build only living area or power stations.
- The player needs to have enough resources available to invest in constructing the building.
- There has to be a need for the new building. If the player's production is sufficient, he does not require another building.

- The ratio between the resources and production has to be observed. As the player is focused on one resource, he must keep the production of the building that produces it higher than the others even though upgrading the others is cheaper. Furthermore he needs to keep the other two mines in certain ratio.

Production Reduction: The AI player reduces the production in mines usually because it is needed to avoid penalizations from energy or population overflow. He reduces the production in all the mines until the required decrease is achieved. The research lab production is kept at 0% except when the AI player needs to do research. In case of the research lab the AI player does not consider the population and energy debt as in case of the other buildings. If he needs to do a research he sets the power in research lab to the required amount and than reduces the production of the other buildings until the debt is avoided. After doing a research the research lab production falls to 0% and the production of other buildings rises to 100%.

Simple Planning: Assuming that the player has enough resources to build more than one building but does not have enough power, he will build a power station. The power station usually requires higher level and takes more time to build than other buildings. Due to these conditions the AI player would not be able to build any other buildings during its construction. Because of this the AI player considers his future population and energy capacity instead of the current (he counts the buildings under construction as if they were finished). Therefore when he starts upgrading the power station the AI player simultaneously starts to upgrade as many buildings as possible. They are often finished before the power station in which case the player lowers the buildings' production until the power station is built in order to avoid an energy debt. However, it is advantageous to build the buildings simultaneously with the power station because that way they are sooner operational. The same principle is also applied to the living area.

Production Regulation: The AI player's secondary mines have much lower production than the main one. The AI player keeps the ratio between the secondary mines and the main one to 2:3 calculated in IPs. The ratio between the secondary mines' productions depends on the availability of the resources in the game and does not depend on the demand of the players because due to our effort to keep the game balanced, the demand for all the resources is forced to be the same.

Rebuilding: As part of some strategies the AI player has the possibility to rebuild his power station. These rebuilds are expensive but may bring income by reducing the building area required. The AI always prefers to rebuild the power station. The possibility of rebuilds depends on research, without which no rebuilds are available.

4.3 Research Selection

In order to make a selection the AI player browses all the types of research and decides which can be upgraded. Unlike the building selection, the selection of research does not depend on energy, population and free space.

Conditions: in order for a type of research to be upgraded, it must satisfy these conditions:

- The Research Lab level must be greater than the current research level, even if the power is reduced.
- The player must have enough resources to invest in making the upgrade.

Strategies The distribution of points fully depends on the AI player's strategy. In each of the strategies it is strictly defined in which direction each research develops.

In the following sections we will discuss how AI players behave in auctions.

5 AI Players Participating in Auctions

In this chapter we will discuss the mechanisms used in the decisions of the AI players in each of the auction types. Firstly we will describe how the player decides when to create an auction, then the rules for choosing an auction if more are available, then the process by which the seller decides when to accept an auction and finally how the bidder decides whether to participate in an auction or not.

5.1 When to Create an Auction

Since each player has one resource on which he primarily focuses, this resource can be taken as a starting point. The time to create an auction can be specified as the time when the player has more of some resource than he needs. Having more than he needs can be defined as the reserve being enough to pay the most expensive upgrade among the buildings, research etc. It is not strategic to create an auction with almost zero resources stack since there is a fixed amount the player must pay to create an auction. It means that the AI player waits until he satisfies the following conditions.

5.1.1 Smart Starting Value

The player has to choose an auction parameter (AP) depending on the progress of the game. The initial idea was that the average auction value can be easily calculated from the last 5 samples, so that the player has one number which should be approximately the auction value. The game needs to go from small to larger amounts, which is why it is necessary to make the AP slightly higher. This can be done for example by counting the highest sample twice or by not using smaller samples than the smallest one.

Ultimately this idea was rejected as problematic. In case of this solution the player would use samples from past auctions to create new auctions that would ultimately become samples as well. This leads to the following problems:

- The bounds are unstable, so the game can lead to wrong values.
- The raising of auctions' prices would be uncontrollable. The growth of the value of the auctions would be uncertain because of probability distribution and the game progress would be changing dramatically from game to game.
- The starting samples would have to be set and the game would have to be continued depending on those values. In such case the starting value would have huge effect on the game.

- The AP would have to be recalculated after each successfully ended auction which is not optimal for implementation.

The solution we used is to take the amount of resources the player will generate in certain time interval as a default value. This setting can be easily controlled. Each player decides without regard to the other players and can create auctions with almost the same time intervals. Therefore the AP is certain, stable and much easier to control. This situation also requires the starting value to be set. Otherwise the AI player would start creating auctions directly from the start, spending a lot of the starting resources and slowing himself down. After reaching the starting value his APs will not depend on it and therefore it can be set with no strong influence on the game.

5.1.2 Exact Value Selection

The type of probability distribution we used in the game is a Gaussian distribution with maximum in the value we have. This causes the probability of selection to be highest in the exact value selected (AP) and on both sides to fall to almost 0. In this way the solution corresponds to reality.
The first step to determine when the player creates an auction is:

$$g^*(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \text{ where } \mu = 0 \text{ and } \sigma = 1.$$

After including all known parameters and shifting the function $g^*(x)$ and applying it to interval $< \frac{2}{3}AP; \frac{4}{3}AP >$ which is the tolerance for the player to create an auction with the Gaussian probability distribution on this interval we get the function $g(x)$:

$$g(x) = \frac{1}{\sqrt{2\pi}} e^{-\left(\frac{7.5(x-AP)}{AP}\right)^2}$$

Then a number x is selected at random from $\langle min(g^*(x)); max(g^*(x))\rangle$, where $Df : g*(x) \in \langle -5, 5\rangle$. Because $g(x)$ is a shifted even function it has no inversion for the whole domain. It must be split into two intervals by randomly generating an $n, n \in \{-1; 1\}$.

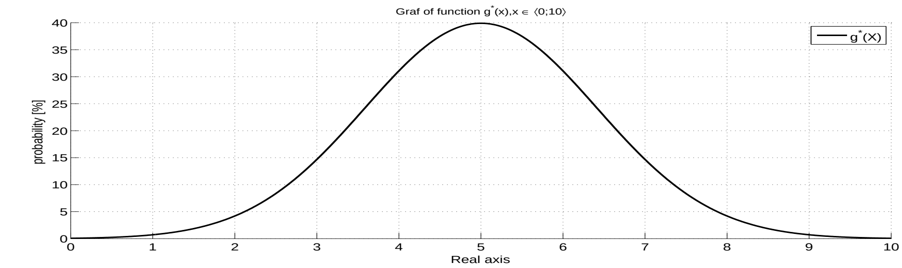

Figure 6: Function $g^*(x)$ for $x \in < 0; 10 >$

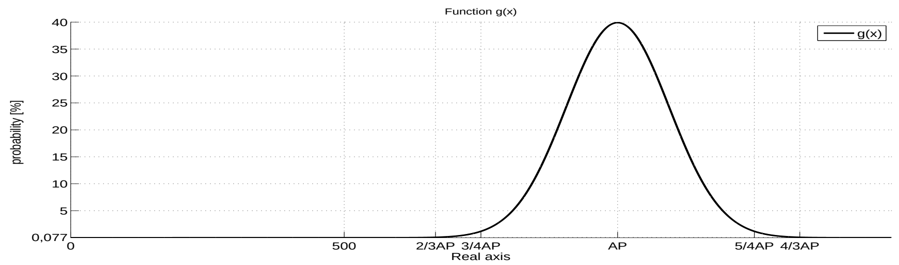

Figure 7: Function $g(x)$, probability distribution of the player's decision

5.2 Choosing an Auction

At any time during the game no more than 5 auctions are revealed to bid. The player bids in every auction allowed, because even if he does not need the resource he can still sell it through direct trade, so there always exists a value for which it is advantageous to bid. Moreover the investment to the unwanted auction is so low that it will not affect the more important investments. Furthermore, the small bid will be quickly overbid by other players so there is no loss of money.

5.3 Seller's Decision

In the setting of the game the auction is often advantageous for the seller even if he sells the resources for slightly less than their expected price (he gets some IPs just for creating the successful auction).Selling an item is advantageous when the sum of the real value of the auction and the small amount needed to create the auction (BA) is bigger than what the seller gains. The seller's income consists of the IP value of the money he earns and 10% of the auction's real value, which is the IP reward he earns for a successful auction [7].
The condition can be expressed as:

if $R_V + BA < ME + 0,1R_V$, where R_V is auction value in IPs and ME is money earned.

As the ratio between money and IPs is 1:1 we can simplify it to

[7] See 2.1 IP distributing

$$BA < 0,1R_V$$

The seller's income s can be expressed as:

$s = HB_V - 0,9R_V - BA$ where HB_V is the value the goods were sold for.

We can see from this equation that if the highest bidder gives the R_V ,the earn of the seller will still be $0,1R_V - BA$.

5.4 Bidder's Decision

In this part of the thesis we will explain how the AI player decides about his bids in auctions. We will also discuss the dependence of private values and risk attitudes.

5.4.1 Risk Neutral Agents with Independent Private Values

Common Values: The simplest way to apprise goods are common values. To calculate common values C_V in the game we first need a real value R_V. R_V is used for translating each of the resources to IPs:

$R_V = a + 1,5b + 3c$, where $a/b/c$ = amount of stones/metals/minerals.

Players usually have to reckon with the income in case of winning the auction which is 10% of R_V. It means that for the game we will calculate C_V as:

$$C_V = R_V + 0,1R_V = 1,1R_V$$

Agents can go as far as this limit, when they want to have profit greater than or equal to 0. Then the winner's income w can be calculated as:

$w = C_V - P$, where P is the payment that the winner must make.

Private Values: The AI players do not use the common values to evaluate the goods. The reason for this is that in such case the players would bid until they reached the same amount and the last player to bid would win the auction because no one else would be able to continue bidding (the values would be the same). Instead, each player calculates his own value of the goods that depends on the common value but can differ significantly.
It is necessary to find the minimum and maximum values that the players will be able to bid. The player bids the minimum in case when he does not need the resources in the auction at all, only to sell them through the direct trade. The minimal bid value can be set as:

$MB = DT_M + 0,1R_V$, where DT_M is the value in money if sold though the direct trade.

The situation with maximal value is rather similar. When it is more advantageous to buy the resource trough the direct trade, the player will buy it there. In the direct trade the player must calculate with the R_V not the C_V as in the auction. The highest bid the player will place is:

$$HB = DT_{RS} + 0,1R_V, \text{ where } DT_{RS} \text{ is the } IP \text{ value of resources from direct trade.}$$

The production increase brought about by the resources from a win in an auction seems to be a great private evaluation for the players. However, usually the investments do not directly affect the production. It might be calculated in certain cases but it would be more complicated than useful. Therefore the need for a resource should depend on three factors:

- The amount of the resource the player already has.
- The time that the player would need to get the amount of resource himself.
- The availability of the resource on global scale.

The solution we used in the game is that the AI player takes into consideration a part of the resources he has (a part because it is a way to avoid coincidence in case he just earned resources from another auction but did not produce them himself) and than measures the time until he will reach the amount offered in the auction by his own production (parameter t). This time is than what matters in setting the private value. The function that calculates the private value has certain conditions that need to be fulfilled:

- The extremes are MB in time 0 and HB in time ∞.
- The function must be increasing in $(0;\infty\rangle$.
- The dependence on time must correspond to reality.

It is better to split the function into a number of intervals since its behaviour differs for each interval. $PV(t) = \left\{ \begin{array}{cc} MB + (CV - MB)\frac{e^t}{e^{t_1}}; & t \in (0, t_1\rangle \\ CV + \frac{0,5CVt}{(t_2-t_1)}; & t \in (t_1, t_2\rangle \\ 1,5CV + \frac{HB-1,5CV}{\pi}(\arctan(t_3 - t_2) + \arctan(t - t_3)) & t \in (t_2, \infty) \end{array} \right\}.$

For the interval $t \in (0, t_1\rangle$ the $PV(t)$ is an exponential function. The reason for this is that it is an interval where the player has enough of the resource and he does not need it at all. He prefers it only if he can trade it without costs. Then, before the time t_1, the need rises and the player starts to ascribe higher value to the resource. The extreme increase is necessary in the last few seconds before t_1. The time t_1 in the figure 8 is set to 20 sec. which is quite a long time but each player can wait this long without high losses.

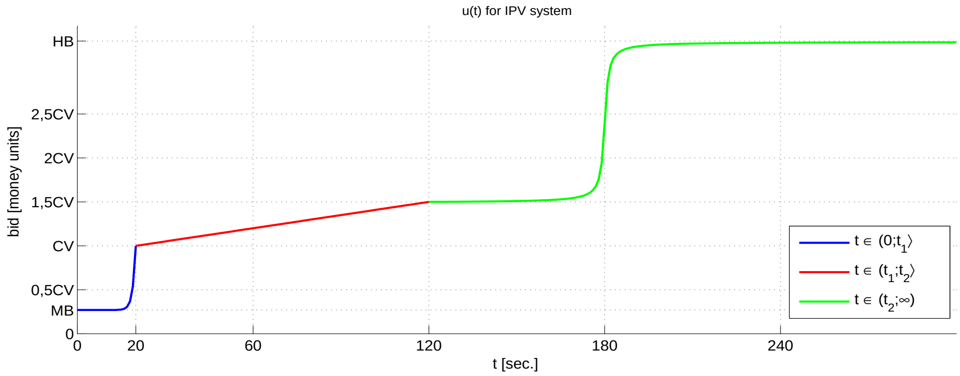

Figure 8: An example of the function $PV(t)$ for IPV,RN case

For the interval $t \in (t_1, t_2\rangle$ the $PV(t)$ is a linear function. Most of the players should be situated in this interval and therefore it is quite long. The increase is linear from CV to $1,5CV$ and the increasing is slow. There is no reason for the increasing to be different around t_1 and t_2. The upper limit of the function is $1,5CV$. Time t_2 in the figure 8 is set to 2 minutes.

The last interval is between t_2 and ∞. This interval includes the next value (t_3) and the function is a kind of arctangent. The third value depends on the inflection point of the arctangent, so the point where the function breaks from almost constant to extremely increasing can be shifted. In this case the exponential could not have been used because the function needs to be converging when $t \to \infty$. In the program the ∞ cannot be reached, so there is a t_4 from which the t is large enough. t_3 in the figure 8 is set to 3 minutes and from 4^{th} minute (in the figure 8) it is counted as ∞.
The availability of the resource is included because MB and HB depends on it.

Utility Function for Independent Private Values: The result of $PV(t)$ is the value the player is able to pay for the goods. The utility function depends on the auction type, because strategies vary. For simplification the utility function (u^*) is normalised for the game (has minimum 0 and maximum 1). The utility function can reach the value under 0 but those values have the same effect as the utility of 0 in risk neutral setting.

<u>English and Vickrey Auction:</u> The best strategy for these two types of auctions is the dominant strategy. (Proof [4],11.1.3) As in the Vicrey auction there is only one chance to bid, the best idea is to bid the PV. In the English auction the player can win sooner than the PV is reached, so the strategy is to raise bids only for a small amount until the PV level is reached or no one continues bidding. The utility function $u(t, b_i) = u^*(t, b_i)$ can be described as:

$$u(t, b_i) = u^*(t, b_i) = 1 - \frac{b_i}{PV}, \text{ where } b_i \text{ is the bid the player is going to offer.}$$

At the moment u^* reaches the PV the utility becomes 0 and then the player refuses to bid more.

Dutch Auction: In the Dutch auction the situation is different. According to MAS [4] the player should suppose his evaluation is the highest since if it were not he would not win the auction in any auction system used. If the player supposes his evaluation is the highest he will pay less than his PV to save money. To win the auction he has to pay the second highest valuation. This system works if the players have the same evaluation of the goods. But in the game the players' evaluations are completely different and each player only knows his own. The utility function will be quite similar to the English one.

$$u(t, b_i) = u^*(t, b_i) = 1 - \frac{EV_{2nd}}{PV}, \text{ where } EV_{2nd} \text{ is the expected value of player with } 2^{nd} \text{ highest evaluation. Expected prices are further discussed in 5.5.3.}$$

The Revenue equivalence theorem says that **for IPV case with neutral agents** the revenue from all the mentioned auction types is the same. It is described in more detail in MAS ([4],11.1.4).

5.4.2 Risk Affected Agents Independent Private Values

In this chapter we will discuss the risk attitude of agents. Certain agents will prefer to enter risky situations more often and to risk more even against the rules of probability. The risk attitudes affect bidding differently in each auction type.

- In English auction the risk seeking player may go further in bidding just to increase the highest bid even though he does not want the goods for such an amount. This either makes the other player pay more than they otherwise would or it leads to winning the auction for a price overstepping the value. Therefore this strategy brings negative outcome either to the opponent or to the player himself. The risk averse players in English auction act as risk neutral but in case they use affiliated values (see 5.4.2) they leave sooner because they are afraid of risk seeking agents. Normally they would leave the auction sooner in case of IPV as well, however as they can see how the bids increase they do not risk anything until their PV is reached. Therefore they can be tricked by the risk seeking agents into offering more but still don't overstep their personal evaluating.

- In Dutch auction the risk attitudes work with different system. The risk attitude in Dutch auction depends on when the player accepts the bid. Because of the strategy that the AI players use, the risk attitude manifests in their underestimating or overestimating the EV of second player. Therefore it is possible for a risk seeking player to win some auctions with smaller loss with the disadvantage of loosing auctions more often. If the EV is underestimated the agent is risk seeking. In case it is overestimated, the agent is risk averse.

- In Vicrey auction not bidding PV is not risky but ineffective because the value for which the goods is sold does not depend on the winner. The risk seeking players prefer to bid more and risk that they can sometimes win the goods for a higher price than they expected to pay. The risk averse players do not bid less than their PV because it would be pointless. The risk averse player in Vicrey auction works as risk neutral even though the values are affiliated.

There another aspect that might affect the risk attitude of the player but is not implemented in the game. It can be explained on the example of two players: one is rich and one is poor. For the rich one it is not risky to spend the maximum amount that the poor one can afford, however if the poor one bids all his money he takes a serious risk. The reason for not implementing this in the game even though it is an interesting idea is that the money investments and incomes change too often and for unpredictable amounts.

For risk dependent agents $u(t, b_i) \neq u^*(t, b_i)$, $u(t, b_i) = u^*(t, b_i) - f(p_i)$. This means that the utility is reduced or raised by the effect of risk attitude. $f(p_i) = \pm(1 - \frac{2b_i/PV}{r_i(2b_i/PV)})$, where b_i is the future bid and r_i are functions from figure 9. The sign depends on the auction type and on the direction in which the risk attitude affects the utility. p_i (payment) in $f(p_i)$ is included as a bid (b_i), because in the game the bid is what the agents have to pay once the auction ends. As the risk seeking and averse strategies change in different auction types the $f(p_i)$ varies too, to be precise the sign is what changes.

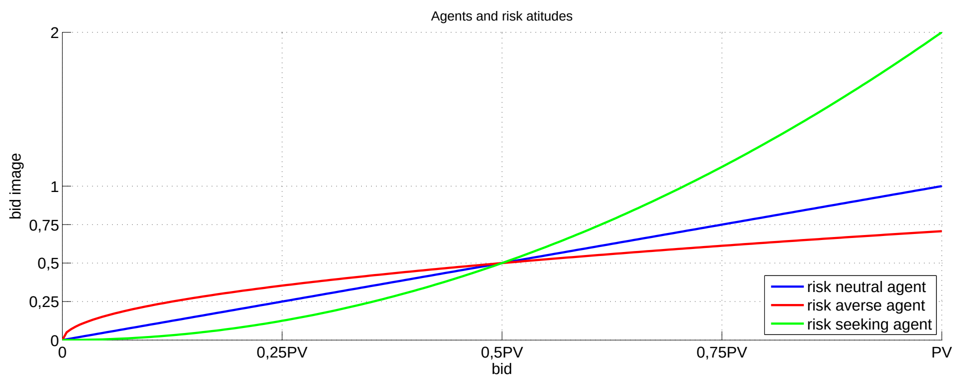

Figure 9: Risk attitudes, curves r_{1-3}

Figure 10 shows the valuation of a bid depending on the PV of the players. In the case of neutral agents the image is exactly the bid. A function $f(r_i)$ is specified with the following conditions:

- $f(r_i) = 0$ for each PV if agent is risk neutral ($n = 1$), it says that the utility function does not change for risk neutral players.
- $f(r_i) <> 0$ for not neutral agents and the value of $f(b_i = PV)$ should be different for agents with different risk attitudes. This explains multiplying by 2. Otherwise if $b_i = PV$ this condition will be false. With coefficient of 2 the risk function $f(r_i)$ works great in the situation when $b_i = PV$ which is fulfilled in the game.

Risk neutrality is represented by the blue line in figure 9. It is a linear function $r_1(x) : y = x$. The risk neutrality does not affect the utility function of an agent, because this equation is always true: $f(p_i) = \frac{2b_i/PV}{r_i(2b_i/PV)} - 1 = \frac{b_i}{b_i} - 1 = 0$. (The example is valid for Dutch auction, for English and Vickrey auctions $f(p_i)_{Vi,En} = -f(p_i)_{Du}$. ($b_i$ is replaced with EV_{2nd} for Dutch auction.)

Risk aversion is represented by the red curve in figure 9.It is $r_2(x) : y = x^n$, where $n < 1$ (for the curve in figure 9 n is set to $0, 5$). The risk aversion reduces the utility function of an agent since the value reaches $PV/2$ and rises it for higher values, because for $\langle PV/2; PV\rangle$ this equation is always true: $f(p_i) = \frac{2b_i/PV}{r_i(2b_i/PV)} - 1 = \frac{2b_i/PV}{(2b_i/PV)^n} - 1 > 0$. (The example is for English auction, for Dutch auction $f(p_i)_{En} = -f(p_i)_{Du}$ and PV is replaced with EV_{2nd} and for Vickrey auction the $f(p_i) = 0$)

Risk seeking is represented by the green curve in figure 9. It is $r_3(x) : y = x^n$, where $n < 1$ (for the curve in figure 9 n is set to 2). The risk seeking rises the utility function of an agent since the value reaches $PV/2$ and reduces it for smaller values, because for $\langle PV/2; PV\rangle$ this equation is always true: $f(p_i) = \frac{2b_i/PV}{r_i(2b_i/PV)} - 1 = \frac{2b_i/PV}{(2b_i/PV)^n} - 1 < 0$. The example is for English and Vickrey auction, for Dutch and Vickrey auctions $f(p_i)_{Vi,En} = -f(p_i)_{Du}$)

if $n \in \langle 0, 84; 1, 14\rangle$ than the results of the utility function change by 10% for both sides. (See figure 10)

Using this in the game an infinite amount of agents with different risk attitudes can be created from just 1 randomly selected number (n_d).

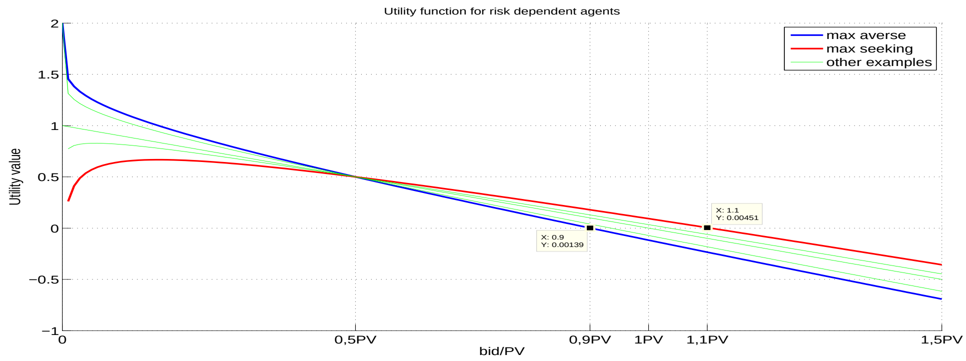

Figure 10: Utility functions for risk dependant agents

Choosing n The n that defines the risk attitude of a player is generated at the start of the game randomly. For the game $n \in \langle 0,84; 1,14 \rangle$ [8]. The probability for risk aversion and risk seeking must be the same. In the interval of the game it means generating whether the player is risk seeking or risk averse and than the exact value.

The revenues from the auctions vary except in case of the risk neutral player. In Dutch auction the revenue for the risk averse player rises but for risk seeking player decreases compared with English and Vickrey auctions. This is because the risk seeking agents estimate the highest opponent's expected value to be lower which means that their utility will be higher if they win but with bigger risk to take. The situation with risk averse players is the exact opposite. The revenue equivalence between English and Vickrey auction remains.

5.4.3 Risk Affected and Dependent Private Values

Expected Value In the next paragraph we will discuss affiliated values. However first we need to discuss how one player (player A) decides about the evaluation of another (player B). These estimated values are called expected values (EV). The EV depends on what each player knows about the others. The information each player has is affected by his espionage technology research:

- The player A has no information:

  If the player A has no information he has to choose a reasonable EV for example the value $1,25CV$. $1,25CV$ is the mean of the longest interval for the function from figure 8.

- The player has information about building's levels:

  If player A has information about the building levels he can calculate the income for each

[8] It influences utility by $\pm 10\%$.

building but with possible fallacy due to research. Nevertheless it is the best assumption player A can make. As the starting value of the resources player A takes the amount of resource that player B generates in t_1 (see 5.4.1) sec. if he has no researches done. The EV can't be exact due to the limits of information player A possesses. At this point we could consider correcting the error margin by the value calculated from the research of player A, however the research levels and directions are so variable that it would not make much sense.

- The player also has information about the other players' resources:
  In this case the player A still cannot calculate the exact income but he knows the real starting value and therefore the EV is much more precise. The problem with income calculation is avoided here because the AI players are limited by programmed behaviour. It can be explained by the spies not being good enough to earn information regularly and precisely.

- The player has all the information about other players' resources and income:
  Since the player A knows all he needs, he can count the EV with accuracy.

Affiliated Values (simplified method) In some cases the value of an object can change only by revealing the scale of demand. Due to this fact for example the value of an item in English auction can rise with each bid. If the demand is high the buyer is ensured that he can sell the goods whenever he wants and therefore he continues bidding over his PV.

Affiliated values should include the others players' expected values into the player's strategy of evaluating goods. It means that the PV of the player depends on the EV of the others. For the game the affiliated value is set as:

$$AV = PV + \sum_{i \neq j}^{n} \beta EV_i, \text{ where } \beta \in \mathbb{R}^n; \beta_i \in \langle \tfrac{0{,}25}{n-1}; \tfrac{1}{n-1} \rangle.$$

As the expected values are not exact β should vary. The value of beta depends on the information the player has and in the game $\beta = \frac{\{1;0{,}75;0{,}5;0{,}25\}}{n-1}$ and in the place of EV_i is $EV_i - PV$, which signifies the differences from the players' expected values. It means that finally:

$$AV = PV + \sum_{i \neq j}^{n} \beta (EV_i - PV), \text{ where } \beta \in \mathbb{R}^n; \beta_i \in \langle \tfrac{0{,}25}{n-1}; \tfrac{1}{n-1} \rangle.$$

In this case the AV is used instead of the PV for the function u. The AV is calculated each time any player is going to bid, not only before the auction as in the preceding cases. For example each time any player in the English auction bids more than the expected value, his expected value is corrected and the other player's AV is recalculated, increasing slightly. The PV and the other players' values stay constant so they do not compensate for the increase of AV and the

AV rises. The same principle works in the Dutch auction. If the goods is not sold yet but the expected value says it should be, the player can adjust his information which leads to a small decrease of AV. Moreover, since for the Dutch auction the player needs the second highest EV, it is also calculated as affiliated.

The revenues in the DPV the case is also different for each auction type. The English auction usually brings the highest revenue compared with IPV as the values are affected one by the other while revealing the demand for the goods. The Dutch auction generates smaller revenue in case of the DPV than in IPV since the seller's income is affected by the concealment of his information. In this case the information is revealed if the item is not bought in at the time when the player expects it. As we have already mentioned, he can than edit the expected value of the player who failed to buy the item, which reduces his own AV.

6 Summary

The result of this thesis is a multi-player game that allows the player to invest in buildings, researches and mines and to improve his city in order to achieve economic dominance. The success in the game depends mainly on the player's ability to sell his resources in auctions and to win the auctions created by the other players. During the game the player should grasp the differences between the various auction systems and observe the behaviour of the artificial intelligence (AI).

With regard to the AI, the player cannot see the processes directing the AI players while playing the normal version of the game. However, this thesis also contains an observer version of the game. In this version the player has a possibility to switch between all the AI players and better observe their behaviour. There are 2 levels of AI players implemented in the game, the beginner and intermediate player each with different building productions and behaviour in auctions.

The multi-player is not implemented in the game since it would require an internet connection for the players, which is not included for time reasons. The game allows for one to eight AI players and one or no real player (the maximum number of players is 8).

An improvement would be to include the statistics of the AI players successes in fighting against human players. It definitely should be a part of the thesis although unfortunately it was not possible to obtain these statistics due to the size of the other parts of this thesis.

7 Future Work

As we have already mentioned in the Introduction, the game offers many possibilities for extension. In this chapter we will mention some of the ways in which further improvements could be realized.

The first major improvement, as already mentioned, would be to finish the multi-player option. The game might be an interesting way of spending time with friends if it included multi-player via internet.

It would also be useful to do some testing of the game in order to bring more balance to it, especially concerning the AI and the balance in research and buildings. Some kind of testing by real players should reveal the main problems and possible disparities. In case of the AI it might be beneficial to write an algorithm to set up the constants more effectively (for example for the PV calculating). In order to achieve balance we only need to change a few values, however what makes this proposition impossible in the present moment is the amount of time that would be spent in testing and statistics.

Another way to improve the game with the information that the testing would bring concerns the graphics environment, which might be more intuitive. Further opportunity to make the game better would be adding transports in the game. Presently the resources in the game are transferred immediately or by neutral transport ships but one of the initial ideas was to give it to the players as another opportunity to gain IPs. It would include building a shipyard, producing ships and also a strategy algorithm determining when it would be advantageous to do so, which would depend on the position of the players around and of the player himself. Considering the dangers which the transporting can posses such as pirates or other players' ships might be an interesting variation. The game could also have the added possibilities of attacking the enemy cities, destroying buildings and ships, as well as investing into defence and stealing resources.

Lastly there is always possibility of further expanding the game by adding new buildings or researches.

8 Conclusion

The game rewards planning, and information inference from the behaviour of other players. Therefore it might be considered an interesting way to effectively learn something about auction algorithms and multi-agent systems. The game also has the potential to become a part of a more complex project, even though the implementation does not always fully support this option.

The environment in the game is competitive and cooperative at the same time. The players compete each other in the effort to maximize their incomes through the trades. They try to win auctions every time it is possible and to create auctions whenever they can. But they also cooperate in a way because each player produces his main resource with the expectation that the others have not had the same idea and therefore he becomes their main source of this resource, and they in turn will have resources that he needs.

This thesis might also be taken as a starting point for others who are interested in AI or multi-agent systems. The AI design can be used in various other works, for example as an easy way to understand the basics of auction protocols or to provide material for others in the field of creating AI.

9 References

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A Contents of the Enclosed CD

Directory	Content description
Game	Last Planet project (implemented game)
Pictures	The pictures from the game
Thesis	This thesis in PDF format.

Table 1: CD contents description